Determination Method of Working System for Deepwater Unconsolidated Sandstone Gas Well Testing

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Abstract

Rapid cleaning up, sand control and gas hydrate prevention are key factors that should be considered in deep-water unconsolidated sandstone gas well testing design. Combined with the feature of pay zone and testing pipe string, the required minimum testing flow rate during cleaning up process was analyzed, afterwards temperature-pressure field model was established for testing process, as well as minimum test flow rate required to prevent hydrate generation was calculated, and then the maximum test flow rate that before sanding was determined according to logging data, finally working system for LSX-N-1 was confirmed based on those critical flow rates. Field application showed that the designed work system effectively provide good guidance for field test operations, no sand production or hydrate generation happened during the test process, a single point of stable flow pressure/production test data was read during productivity test, and complete build-up curve was recorded, consequently the goal of test operation was achieved.

Keywords

Deepwater; DST; Unconsolidated Sandstone; Gas well; Gas Hydrate; Sanding

1. Introduction

As the key segment, well testing has a decisive effect on the discovery of oil and gas fields and formulation of development plan [1]. Different from the conventional testing, deepwater testing should take the formation condition of gas hydrate and control into consideration [2-8], and higher development needs higher deliverability which increases the difficulty and risk of testing. For deepwater unconsolidated sandstone gas wells, if the testing working system is not designed properly, it will lead to hydrate blocking the testing string causing major engineering accident, and also lead to serious sand production resulting in coefficient A and B of productivity equation being not constant and poor dependability of productivity equation [9-10], seriously affecting the discovery and accurate evaluation of deepwater reservoir. So based on the characteristic of testing gas horizons and testing strings in deepwater exploration well LSX-N-1, critical testing flow of clean-up carrier liquid, critical flow of hydrate generation and maximum testing pressure difference and flow of sand production are analyzed, and proper testing working system is designed according to the critical testing flow. Field application indicates that the testing working system designed according to the critical testing flow can effectively prevent hydrate generation and sand production escaping the testing risk drastically and gaining good achievement.

2. Research background

Well LSX-N-1 is located in the Block B of structure LSX-N of Qiongdongnan Basin, with target water depth of 1447m and submarine mud temperature of 3~4℃. All the gas horizon I, II, IV of Huangliu Formation in well LSX-N-1 show good evidences of oil and gas with the depth of abnormal gas logging sandstone up to 64.0m and the depth of logging interpretation gas horizons up to 53.4m. For acquisition of the reservoir parameter of physical property, deliverability and liquid in the structure LSX-N-1, testing operation is preceded in gas horizon I_{botton} in view of its thick gas horizon, good physical property, not drilling bottom water and mass reserves.

The buried depth of gas horizon I_{botton} is between 3321.0 and 3351.0m with logging permeability of 239.6 mD and unconsolidated sandstone. Offshore testing experience in analogous unconsolidated sandstone indicates that testing effective permeability is always higher than logging permeability and testing deliverability is high which is difficult to pull away the flowing pressure difference and can result in sand production. In the gas reservoir, the content of CO_2 is 0.4%, $C_1$is 89.961%, C_2 is 4.843%, C_3 is 2.23%, and other components is 2.566%. The gas formation volume factor under initial formation pressure is 3.283×10^{-3} m^3/m^3, viscosity is 0.031 mPa s, and coefficient of compressibility is 0.0137 1/MPa.

3. Critical gas flow rate of well testing

To avoid damage on formations when testing, besides co-harmonization with different production purpose, producing method and Supply and demand relations, proper testing flow should also meet the requirements as follows: avoiding damage on downhole and reservoirs, deformation on reservoirs and mass sand production in testing wells; no gas hydrate generating when testing; testing flow with enough liquid carrying capacity.

$$\max(Q_{\text{lim}}, Q_{\text{wc}}) < Q_{\text{r}} < \min(Q_{\text{s}}, Q_{\text{y}}) \tag{1}$$

In the formula: Q_{lim}-minimum deliverability of carrier liquid, m^3/d; Q_{wc}-minimum deliverability without hydrate, m^3/d; Q_{s}- maximum deliverability without sand production, m^3/d; Q_{y}-critical deliverability without reservoir deformation, m^3/d.

3.1 Critical liquid carrying flow rate

Well cleanout should be done quickly and the liquid loading (testing liquid and cush) in bore holes should be blowing off in the initial test, and the minimum air-speed needed is:

$$v_c = 1.912\frac{\sigma^{0.25}(\rho_L - \rho_g)^{0.25}}{\rho_g^{0.5}} \tag{2}$$

In the formula: σ-surface tension of blew off liquid, mN/m; ρ_L-the density of downhole liquid loading, kg/m^3; ρ_g-air density, kg/m^3.

Though the cross section area of test strings is A, the minimum flow needed to blow off the liquid loading is:

$$q_c = \frac{3.06 p v_c A}{TZ} \tag{3}$$

And the formula of surface tension is:

$$\sigma(T) = \frac{1.8\times(137.78 - T)}{206}\left[\sigma(23.33) - \sigma(137.78)\right] + \sigma(137.78) \tag{4}$$

In the formula: $\sigma(23.33)=76\times e^{-0.0362575p}$, $\sigma(137.78)=52.5-0.87018p$.

With the formation pressure of testing section being 39.08Mpa, temperature being 77℃, density of liquid loading being $1300kg/m^3$, relative density of gas being 0.6636, radius of testing strings being

0.0428m and gas deviation factor being 0.98, the minimum testing flow needed by carrier liquid is computed to be $1.93\times10^4 m^3/d$.

3.2 Minimum testing flow without hydrate

Coupling prediction model of pressure and temperature

Testing well LSX-N-1 can be divided into 3 parts: air section with height of 29.6m, sea water section with depth of 1447.2m and formation section with mud temperature of 3-4℃ (Fig.1), and borehole temperature -pressure model is published for predicting the area where hydrate generates when testing.

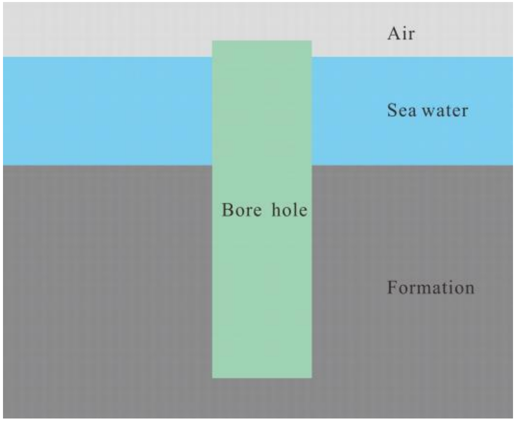

Fig.1 Cartogram of testing well

The borehole mode of heat transfer in formation section consists of convection heat transfer between borehole liquid and casing pipes, heat conduction of cement mantle and that of formations which can be formulated by mathematical model as follows:

$$\frac{dq}{dz} = -\frac{2\pi r_{to} U_{to1} K_e}{w_1\left(K_e + T_D r_{to} U_{to1}\right)}\left(T_f - T_e\right) \tag{5}$$

$$U_{to1} = [\frac{1}{h_c + h_r} + \frac{r_{to}\ln(r_h / r_{co})}{K_{cem}}]^{-1} \tag{6}$$

In the formula: T_D-dimensionless temperature; U_{to1}-overall coefficient of heat transfer of formation section; h_c-coefficient of convection heat transfer of annular flow, W/(m^{2}·℃); h_r-coefficient of heat radiation of annular flow, W/(m^{2}·℃); r_{to}-external radius of oil tubes, m; r_h-external radius of cement mantle, m; r_{co}-external radius of casing pipes, m; K_{cem}-coefficient of heat conductivity of cement mantle, W/(m^{2}·℃).

Because there is only small annular space between oil tubes and the section of sea water and air, and liquid in it is not flowing, thermal resistance of conduction between the oil tubes and intermediate casing pipes can be negligible which can be formulated by mathematical model as follows:

$$\frac{dq}{dz} = -\frac{2\pi r_{to} U_{to2}(t_f - t_e)}{w_t} \tag{7}$$

$$U_{to1} = \left[\frac{1}{h_c + h_r} + \frac{r_{to}}{r_{co} h_w}\right]^{-1} \tag{8}$$

In the formula: U_{to2}-overall coefficient of heat transfer of sea section; h_c-coefficient of convection heat transfer of annular flow, W/(m^{2}·℃); h_r-coefficient of heat radiation of annular flow, W/(m^{2}·℃); r_{to}-external radius of oil tubes, m; r_{co}-external radius of casing pipes, m; h_w-coefficient of convection heat transfer between sea water or air and marine riser, W/(m^{2}·℃).

Borehole pressure is mainly controlled by energy loss caused by friction, alternation of potential energy and kinetic energy which can be formulated as follows:

$$-\mathrm{dp} = \tau_f dh + g\rho_m dh + \rho_m v_m dv_m \tag{9}$$

In the formula: p-pressure, Pa; τ_f –gradient of friction loss, Pa/m; h-depth, m; g- acceleration due to gravity, m/s^2; ρ_m-density of mixture, kg/m^3; v_m-flowing velocity of mixture, m/s.

Coupling temperature and pressure, formula (9) can be transformed as follows:

$$\begin{cases} \dfrac{dT_f}{dz} = -A\left(T_f - T_e\right) - \dfrac{g}{C_{pm}} - \dfrac{v_m}{C_{pm}}\dfrac{dv_m}{dz} + C_{Jm}\dfrac{dp}{dz} \\ \dfrac{dp}{dz} = -\rho_m g - \rho_m f_m \dfrac{v_m\left|v_m\right|}{2D} - \rho_m v_m \dfrac{dv_m}{dz} \end{cases} \tag{10}$$

In the formula:

$$A = \begin{cases} \dfrac{2\pi r_{to} U_{to1} K_e}{C_{pm} w_t (K_e + t_D r_{to} U_{to1})} & \text{Formation section} \\ \dfrac{2\pi r_{to} U_{to2}}{C_{pm} w_t} & \text{Sea water/air section} \end{cases} \tag{11}$$

Parameter A of formation and sea water/air section in formula (11) can be mark out F_1 and F_2, and they are the function among well length z, Pressure p and temperature T:

$$\begin{cases} \dfrac{dp}{dz} = F_1(z, p, T) \\ \dfrac{dT}{dz} = F_2(z, p, T) \end{cases} \tag{12}$$

The downhole pressure and temperature are adopted, as initial point, to compute the formula:

$$\begin{cases} p\left(z_0\right) = p_0 \\ T\left(z_0\right) = T_0 \end{cases} \tag{13}$$

Fourth-order Runge-Kutta method is adopted to compute the above differential equation.

Critical flow of hydrate generation

According to the temperature-pressure field model of borehole, borehole temperature under different gas flow rate is computed (Fig.2). When the flow is zero (well off), the downhole section above 1981m is in the hydrate stable zone, and the maximum degree of super-cooling is near the mud surface with temperature of 23℃. When the flow is between 5×10^{4}m^3/d and 25×10^{4}m^3/d, there will be a certain hydrate stable zone, however, the whole borehole can avoid generating hydrate with the flow more than 25×10^{4}m^3/d. So the minimum testing flow avoiding generating hydrate is 25×10^{4}m^3/d.

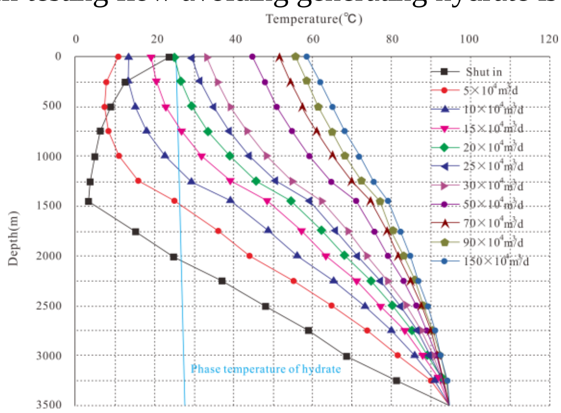

Fig.2 temperature field in bore hole with different flow velocity

3.3 Maximum testing flow without sand production

The minimum critical testing pressure difference which leads to sand production in reservoir and reservoir damage is presented as follows [2]:

$$\Delta p_{sf} = C_1 \tan(\frac{\pi}{4} + \frac{\phi}{2}) \tag{14}$$

$$\Delta p = C_2 - \frac{2\nu}{1-\nu}(10^{-6}\rho gH - P_e) \tag{15}$$

In the formula: Δp_{sf}-critical pressure difference of sand production in formations, Mpa; Δp-critical pressure difference of formation damage, Mpa; C_1-rock cohesion, Mpa; Φ-angle of internal friction, °; C_2-rock compressive resistance, Mpa; v-Poisson ratio; ρ-rock density, g/cm^3; H-depth of reservoir, m; P_e-formation pressure, Mpa.

As showed in Fig.3, after mechanical parameters computed by logging data [10], the maximum pressure difference of sand production in testing section of well LSX-N-1 is 1.5Mpa, that of formation damage is 1.96 Mpa, and numerical analogue indicates that the maximum testing flow is about 173.7×10^{4}m^3/d when apparent skin factor is 10.

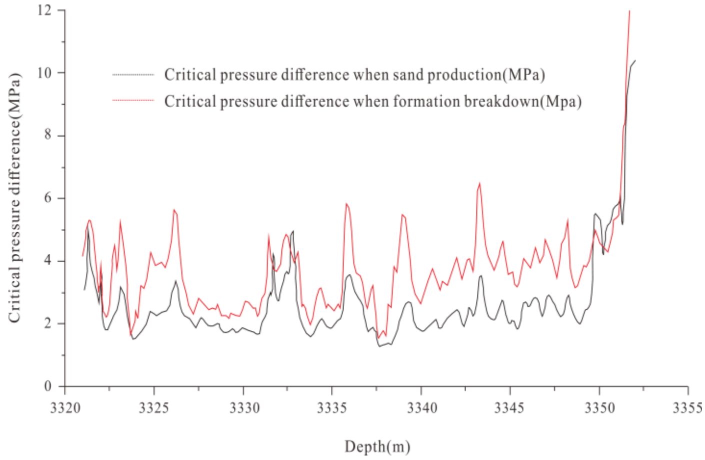

Fig.3 the critical pressure difference in test section when formation breakdown and sand production

4. Design of working system

Based on the analysis, the critical testing flow in well LSX-N-1 is between 25×10^{4}m^3/d and 173.6×10^{4}m^3/d. Considering that platform HYSY981 is of testing capability of 200×10^{4}m^3/d and only between 120×10^{4}m^3 and 160×10^{4}m^3/d can the single well allocation meet the requirement for deepwater development, combined the geologic analysis, deliverability working system is designed (Table1).

Table1 Production test program of LSX-N-1 well

Working system	Choke size (mm)	Gas flow(10^{4}m^3/d)	Yield time(h)
Initial open	14.29	70	10
	9.53	40	7
	19.05	110	7
	23.81	150	7

5. Field application

After reservoirs in well LSX-N-1 are perforated, hydrate proofing methanol is injected into the testing system before chock manifold respectively under the mud surface, on the mud surface and above the earth surface, and the adjustable bean is opened to put through quick well cleanout, which restrains the generation of hydrate effectively. Then beans with radius of 12.70mm, 9.53mm, 19.05mm and 25.40mm are adopted to compute production, and as showed in Fig.4, the testing flows of different beans are $74.29\times10^4 m^3/d$, $48.29\times10^4 m^3/d$, 123.73×10^4 m^3/d and $160\times10^4 m^3/d$ respectively; then after well off for 34h, pressure build-up test is done which is the same with the designed, the flow pressure of individual stationary point/the data of production test point have been recorded and the complete curves of build-up testing have been investigated, which constitute the complete testing data (Fig.4).

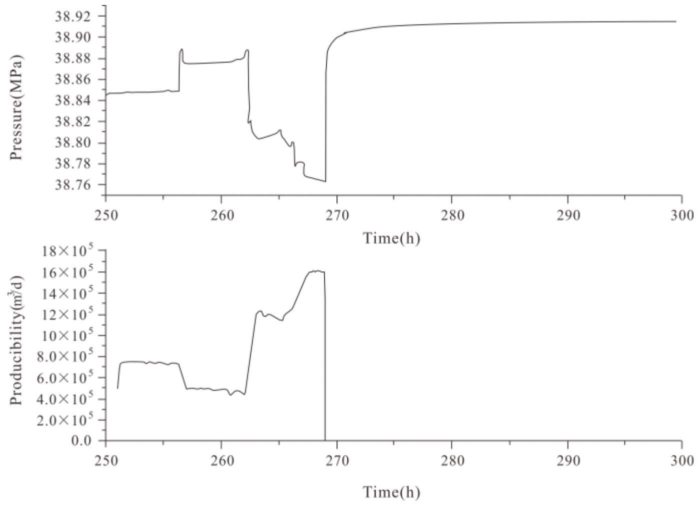

Fig.4 History matching of test pressure for LSX-N-1 well

Pressure recorded by manometer outside screen pipe and log-log plot of pseudopressure and differential of pseudopressure are showed in Fig.5, and the log-log plot is of good quality indicating that edge characteristic shows up after undergoing evident radial flow. Data interpretation indicates that the effective permeability of gas horizon is 565mD, total skin factor is 0.78 and wellbore storage coefficient is $0.0488m^3/Mpa$, combined with geological understanding, the gas/water boundary is about 1200m and the lithologic boundary is about 880m and 940m, which can clearly block out the gas range of testing reservoir.

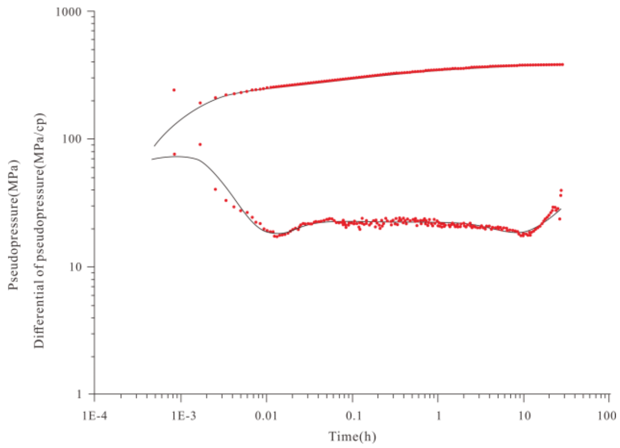

Fig.5 Pressure - ressure derivative double logarithmic curve

There is no hydrate generating during testing and no sand production in formations, which indicates that the method of designed testing working system based on critical testing flow is reasonable and feasible.

6. Conclusion

(1)The critical carrier liquid flow, generation area of hydrate and critical flow, critical pressure difference and flow of sand production in gas wells are published when testing deepwater gas wells.

(2) By analyzing the critical testing flow, working system deepwater testing has been designed, engineering the field conduct effectively and decreasing the operating risk of deepwater testing.

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